AN ELECTRONIC ANALOG FOR TORSIONAL VIBRATIONS

ANTON CHARLES HANSMANN

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Professor Earl B. Millard
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge 39, Massachusetts

Dear Sir:

In accordance with the requirements for the degree of Naval Engineer, I submit herewith a thesis entitled, "AN ELECTRONIC ANALOG FOR TORSIONAL VIBRATIONS".

Respectfully,

ANTON C. HANSMANN
Lieutenant, U. S. Navy

ACH/ma

AN ELECTRONIC ANALOG FOR TORSIONAL VIBRATIONS

by

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B. S., United States Naval Academy
(1945)

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(1948)

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Department of Naval Architecture and Marine Engineering, May 25, 1953

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H204

ABSTRACT

AN ELECTRONIC ANALOG FOR TORSIONAL VIBRATIONS

by

ANTON C. HANSMANN

Submitted to the Department of Naval Architecture and Marine Engineering on May 25, 1953 in partial fulfillment of the requirements for the degree of Naval Engineer.

The object of this thesis is the design and construction of an analog computer primarily for the investigation of torsional vibrations in marine geared propulsion systems.

The computing sections have been built, utilizing the George A. Philbrick Researches Co. K2-W plug-in operational amplifiers as the basic computing elements. Provision has been made for the easy addition of reset and initial condition setting circuits so that the computer as built may be converted, with a minimum of labor, into a general purpose d-c analog computer suitable for the solution of a wide range of physical problems.

By means of simple voltage measurements at appropriate points resonant frequencies and values of torque amplification may be readily obtained. The effects of variations in system constants may be observed by merely changing coefficient settings on the computer.

Before the computer which has been built may be placed in operation, it will be necessary to design and construct a well regulated, heavy duty power supply.

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INTRODUCTION

The solution of a large number of scientific and engineering problems is possible only after detailed numerical computations. It is true that in many cases where only a single calculation has to be performed, it is not practicable to construct an analog to do the job. However, in some fields of engineering, some mechanical circuit problems occur over and over. A prime example is the case of the torsional oscillations of ship propulsion equipment. The importance and complexity of the problem have been demonstrated by the large number of papers discussing special methods of attack and debating the relative merits of different propulsion systems. (1)

The burden of computation can be lightened by the use of some type of analogue which will indicate solutions rapidly and with sufficient accuracy. In the past some use has been made of a.c. network analyzers to represent marine propulsion systems, but there use does involve difficulties, particularly with regard to inductors.(2) A preliminary investigation was made of the possibility of building an electrical analog, but this approach was abandoned when it became evident that it would be necessary to design and build the inductors required, since those with the required characteristics were not available from standard commercial sources at reasonable cost. The advent of the George A. Philbrick K2-W operational amplifiers on the market made the use of an electronic analogue attractive. All additional components required are available from stock with one percent accuracy at reasonable cost.

In electronic analog computers, the variables are represented by voltages which vary with time.(3) Time is generally used as the independent

variable. These computers are capable of solving complicated mathematical problems by means of such simple electrical circuits as d-c amplifiers and potentiometers.

Compared with most mechanical and electromechanical analog computers, the d-c analog computers are relatively cheap, easy to operate and maintain, and capable of flexible interconnections by means of simple patch cords. Perhaps the outstanding advantage of a d-c analog computer is the fact that it can usually be constructed from standard store-bought electronic parts by well-known radio assembly techniques, without any precision machine shop work.

Practical d-c analog computers may be highly specialized or very flexible. The computer which has been built is flexible, all connections between computing elements being made by patch cords, affording a device capable of solving any physical problem involving eight orders of differentiation employing constant coefficients. Parameters and coefficients given by the problem can be changed very conveniently by means of calibrated dials on the front panels of the machine. This is particularly useful in many engineering applications where trial solutions for different coefficient settings are used to obtain optimum design parameters.

The solution of a set of ordinary differential equations on a d-c analog computer proceeds as follows:

1. With the machine connected to solve the given problem, the machine variables (voltages) are set to the correct initial conditions prescribed by the problem.
2. The computing elements are then made operative and force the voltages in the machine to vary in a manner prescribed by the given differen-

tial equations. The voltage variations with time are recorded and constitute solutions of the given problem.

3. The machine is stopped at a time chosen by the operator. The maximum computing time is usually determined by limitations of the computing elements. The machine is at once reset to its initial condition and is ready for the next run with changed, coefficients, initial conditions, etc. In an alternative method the solution is repeated automatically by electronic or relay switching at a rapid rate so that the results may be observed on the screen of a cathode ray oscilloscope.

The operation of the computer which has been built will not be exactly as outlined above, since it has been designed, for the present, with the purpose of solving torsional vibration problems in the steady state. This being so, it is not necessary to insert initial conditions other than insuring that the d-c output of all computing elements is zero at the start of a run. However, sufficient room is left to permit the addition at a later time of reset and initial condition setting equipment.

PRINCIPLES OF OPERATION OF ANALOG COMPUTERS

The problems solved by analog computers usually deal with the behavior of a number of variables. The aim is to determine how these variables change with time, and, in the case of torsional vibrations, with frequency, or with another independent variable under certain conditions. The particular conditions imposed by each problem are usually given as a set of mathematical relations or equations.

The variables are represented in the d-c analog computer by corres-

ponding voltages, or machine variables X_1, X_2.... X_n. In usual practice these machine variables are simply proportional to the corresponding original variables on a convenient scale. The given relations between the original variables are now expressed by an analogous set of relations between the machine variables.

Figure 1 shows schematically how relations are represented in a d-c analog computer. The voltage X_2 will appear as the input voltage of a block of computing elements which takes it into consideration and produces X_1 as an output voltage. This output voltage will be the desired function of the input voltage X_2 if the correct combination of computing elements has been used. Note that, in general, the relation produced by the block in Figure 1 is unilateral, that is changes in the output voltage X_1 will not produce changes in the input voltage X_2 unless additional connections and computing elements are used.

In many cases an output voltage will appear as a function of several other machine variables. The block of computing elements producing the output desired will have more than one input voltage, the effects of the different input voltages being mixed to produce the correct functional relation.(see Figure 2)

If two or more simultaneous relations between machine variables are given each equation is solved electrically for a different variable. This variable appears as the output voltage of a block of computing elements. Figure 3 shows how it is then used as an input voltage for the computing elements establishing the other equations. The resulting interconnections force the machine variables to satisfy all the given relations.

It is easily seen that a majority of problems in applied mathematics

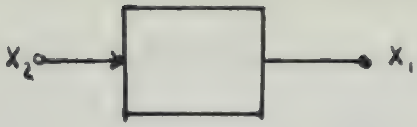


FIG. 1

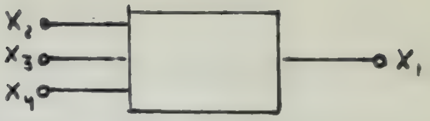


FIG. 2

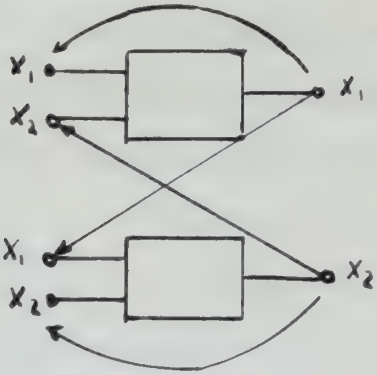


FIG. 3

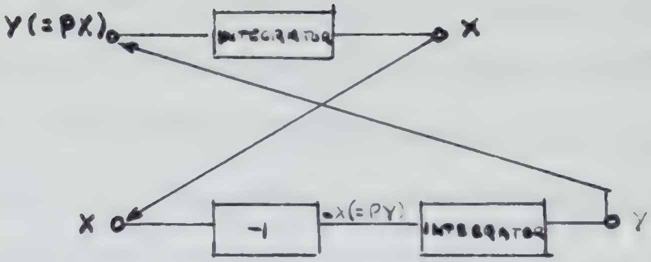


FIG. 4

require a description of changes of quantities involved in physical processes. A time derivative like dX/dt is a quantitative measure of a change dX; the latter is compared with the corresponding change of a known physical quantity, the time t indicated by a clock. It is practical to write $d\ /dt = P$ and $dX/dt = PX$. This notation will be used throughout this paper. For example, if $X = \cos wt$ then $PX = P \cos wt = -w \sin wt$. The second derivative of X may be expressed as P^2X, higher derivatives being defined accordingly.

In problems such as torsional vibrations a set of differential equations is given, and it is desired to find the corresponding time dependence of the variables involved. The set of differential equations is solved when all the variables are computed as functions of time. Thus the set of differential equations

$$PX = Y \qquad\qquad PY = -X$$

is satisfied by the functions

$$X = C \sin (t + \Theta) \qquad\qquad Y = C\cos (t + \Theta)$$

where C and Θ are arbitrary constants.

Figure 4 shows how relations of this type may be represented on d-c analog computers. All derivatives of machine variables are represented by voltages in the machine and are themselves machine variables. The figure also shows how special computing elements called integrators form the time integrals of the voltages proportional to the derivatives PX and PY to obtain the machine variables X and Y. With this arrangement the machine variables X, Y, PX and PY must vary as prescribed by the given mathematical relations. Records of X and Y will then constitute a solution of the set of differential equations. Analog computers capable of solving sets of ordinary differential equations are often referred to as differential analyzers.

One cannot overemphasize the usefulness of the block representation of mathematical relations in practical computer applications. This representation serves as an instructive model which illustrates relationships between different variables of a problem. In many applications the functional resemblance between the model and the actual equipment described by the mathematical relations is striking. In the analog computers the actual relations between variables become alive and can be observed directly. The next task is that of designing generally useful building blocks or computing elements.

It will be desirable to make a computing machine easy to construct and suitable for a wide variety of applications. It is customary to perform more complicated mathematical operations on the computer voltages through combinations of a limited number of simple operations, performed by basic computing elements. A very wide range of problems can be solved conveniently by the application of only the following computing elements:

1. Devices which will multiply a machine variable by a constant coefficient
2. Devices which will generate the sum of two or more machine variables
3. Devices which will generate the product of two machine variables
4. Devices which will generate functions of machine variables
5. Devices which will generate either the time integral or the time derivative of a machine variable.

In the computer built items 3 and 4 are not included, though it may be desirable in the future to include 4 as the dampings involved in marine propulsion systems are non-linear.

Compared with many other computing devices, d-c analog computers are

often strikingly simple. The reason for this is in the relative ease with which the fundamental operations of multiplication by constants, addition, differentiation, and integration can be performed by utilizing simple basic laws of current flow.

Figure 5 shows how a simple voltage divider or potentiometer is used to multiply a voltage by a constant positive coefficient a $(1 \geq a \geq 0)$

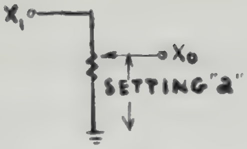
$$X_0 = aX$$

The coefficient setting may be read on the potentiometer dial. The dial scale will be linear unless the potentiometer is loaded appreciably by another computing element connected to its output terminals.

D-c amplifiers with feedback make it possible to multiply a d-c voltage by a constant greater than 1. The operational amplifiers used generate an output voltage whose sign will be the opposite of that of the input voltage. The feedback amplifier thus multiplies by a negative constant; it acts as a phase inverter.

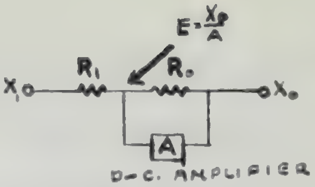
D-c amplifiers with various feedback networks are used extensively in d-c analog computers. They are often referred to as operational amplifiers. The transfer functions of such devices are determined mainly by the feedback networks; the amplifier forward gain is usually made as high as possible in order to make the transfer function stable. The amplifiers and their associated power supplies are designed for low drift. All input and output voltages are measured with respect to a ground reference. It is clear that the output voltages of the operational amplifiers must not exceed certain limits corresponding to the range of linear amplifier operation. In the case of the K2-W operational amplifiers this limit is plus and minus 50 volts.

Figures 5 thru 9 illustrate the various basic computing elements which



$X_o = aX_1$

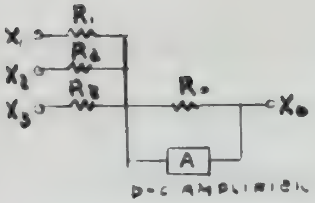
FIG. 5



$X_o \approx \frac{R_o}{R_1} X_1$

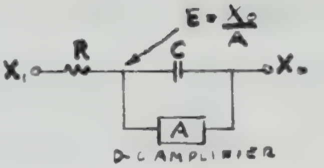
MULTIPLICATION BY
CONSTANT COEFFICIENT

FIG. 6



$X_o \approx -R_o \sum \frac{X_i}{R_i}$

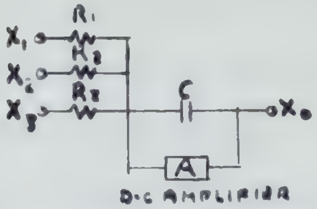
FIG. 7



$X_o \approx -\frac{1}{RCp} X_1$

INTEGRATION

FIG. 8



$X_o \approx -\frac{1}{Cp} \sum \frac{X_i}{R_i}$

SUMMING INTEGRATOR

FIG. 9

were used in the torsional vibrations analog together with their transfer functions.

THE TORSIONAL VIBRATION PROBLEM

In most ships the prime mover, propeller and power transmission system constitute an oscillatory system. Thus the pulsating torques which are produced by the propeller and sometimes by the prime mover may under certain resonance conditions produce trosional vibrations of large amplitude. It is therefore always necessary to investigate any proposed design to insure that the maximum torques developed under any operating condition will not exceed reasonable values. Resonance may occur at one or more speeds with almost any type of propulsion system.

The evaluation of these oscillatory torques is straightforward and simple in principle, but very laborious and time consuming in practice. It is the purpose of the computer which has been designed to provide a rapid means of determining the curves of torque amplification versus frequency of the exciting torque simply and directly by means of measurements made at appropriate points in the analog. In addition to eliminating the necessity of solving the equations of motion, as in the case of a mechanical drive wherein the equivalent shaft spring gradients and damping coefficients are constant or simple functions of frequency, the computer will permit the solution to other types of drive wherein damping coefficients and spring gradients are variable and not simple functions of frequency. It will also be possible, using the computer to determine the transient response of the propulsion system.

PROCEDURE

As is well known, the typical propulsion system of Figure 10 may be reduced to a single speed equivalent as shown in Figure 11. This is the system for which the analog has been designed. However, provision has been made so that by the addition of a few more K2-W operational amplifiers and a small number of components the system shown in Figure 12 may be simulated, this configuration permitting a more detailed analysis of oscillatory behavior.

The equations of motion for the system of Figure 11 are as follows:

$$J_1\ddot{\theta} + B_1\dot{\theta} + B_a(\dot{\theta}_1 - \dot{\theta}_2) + K_1(\theta_1 - \theta_2) - M_{af} = 0 \qquad (1)$$

$$-J_2\ddot{\theta}_2 - B_2\dot{\theta}_2 + B_a(\dot{\theta}_1 - \dot{\theta}_2) + B_b(\dot{\theta}_3 - \dot{\theta}_2) + B_c(\dot{\theta}_4 - \dot{\theta}_2) + K_1(\theta_1 - \theta_2) \qquad (2)$$

$$+ K_2(\theta_3 - \theta_2) + K_3(\theta_4 - \theta_2) = 0$$

$$J_3\ddot{\theta}_3 + B_3\dot{\theta}_3 + B_b(\dot{\theta}_3 - \dot{\theta}_2) + K_2(\theta_3 - \theta_2) = 0 \qquad (3)$$

$$J_4\ddot{\theta}_4 + B_4\dot{\theta}_4 + B_c(\dot{\theta}_4 - \dot{\theta}_2) + K_3(\theta_4 - \theta_2) = 0 \qquad (4)$$

Where:

M_{af} = Applied torque

J = Mass moment of inertia in pounds-inches-seconds^2

B = Damping constant in pounds-inches-seconds/radian

K = Shaft spring constant in pounds-inches/radian

First and second derivatives are indicated by . and .. respectively.

The problem now is to set up an analogue whose behavior will represent the above equations of motion. To illustrate the procedure to be followed a simple 2 storage torsional system will be put into block diagram from and

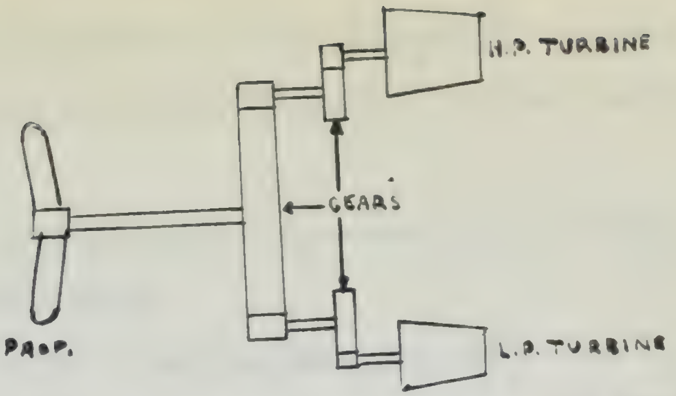


FIG. 10 TYPICAL PROPULSION SYSTEM

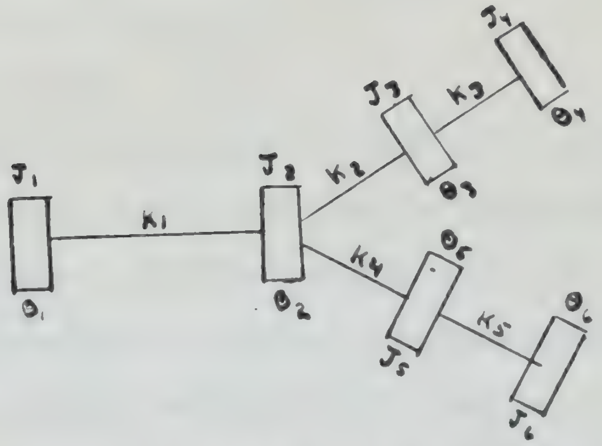


FIG. 12 SIX MASS EQUIVALENT

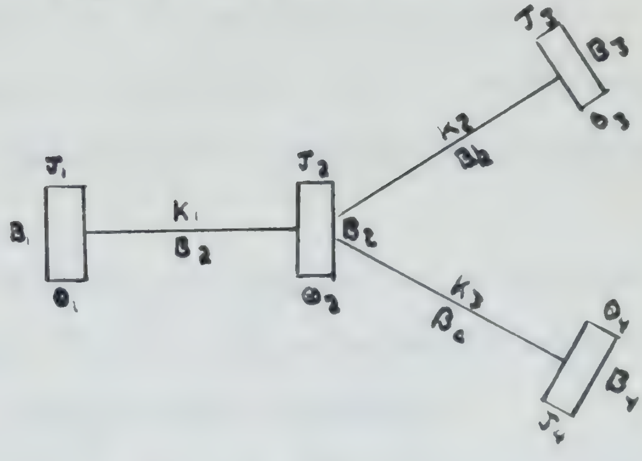


FIG. 11 FOUR MASS EQUIVALENT

the procedure for determining scale factors will be demonstrated. The process to be used for the entire problem will be a simple extension of that to follow.

Figures 13 and 14 show the mechanical system and its equivalent mechanical block diagram.

The equation of motion for the system is:

$$J\ddot{\Theta} + B\dot{\Theta} + K\Theta = M \qquad (5)$$

That the operational system in Figure 14 applies may be seen by rewriting equation 5 as follows:

$$M - K\Theta - B\dot{\Theta} = J\ddot{\Theta} \qquad (6)$$

From what has been said previously about the operation of the various computing elements, it can be seen that the correspondence shown in Figure 15 is obtained. The blocks labeled with a K and a subscript represent the scale factors of equivalence between mechanical values and the corresponding electrical voltages in the computer, e.g. $\Theta = k_\Theta e_\Theta$.

There are a number of ways in which the problem of scale factors and coefficient setting may be handled. (3,4,5)

The method to be used in this paper is one recently developed by Professor J. B. Reswick of the Massachusetts Institute of Technology and described in (4).

Consider the system of Figure 15 to be a "real-time scale" analog. T equals one second. All C's will be numerically equal to the coefficients of the mechanical system that they represent.

Each voltage will now represent its analogous variable in such a way that one volt equals one unit, e.g. if e_Θ represents a rotational velocity Θ in radians per second, then one volt of e_Θ represents one radian per second

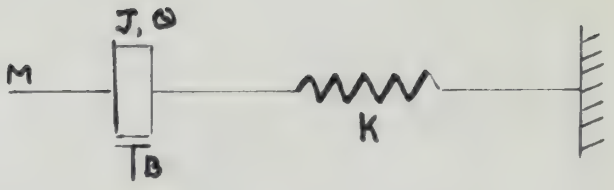


FIG 13 TWO STORAGE SYSTEM

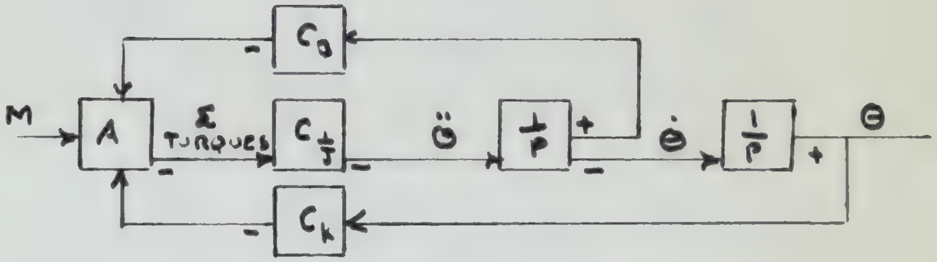


FIG 14 OPERATIONAL BLOCK DIAGRAM

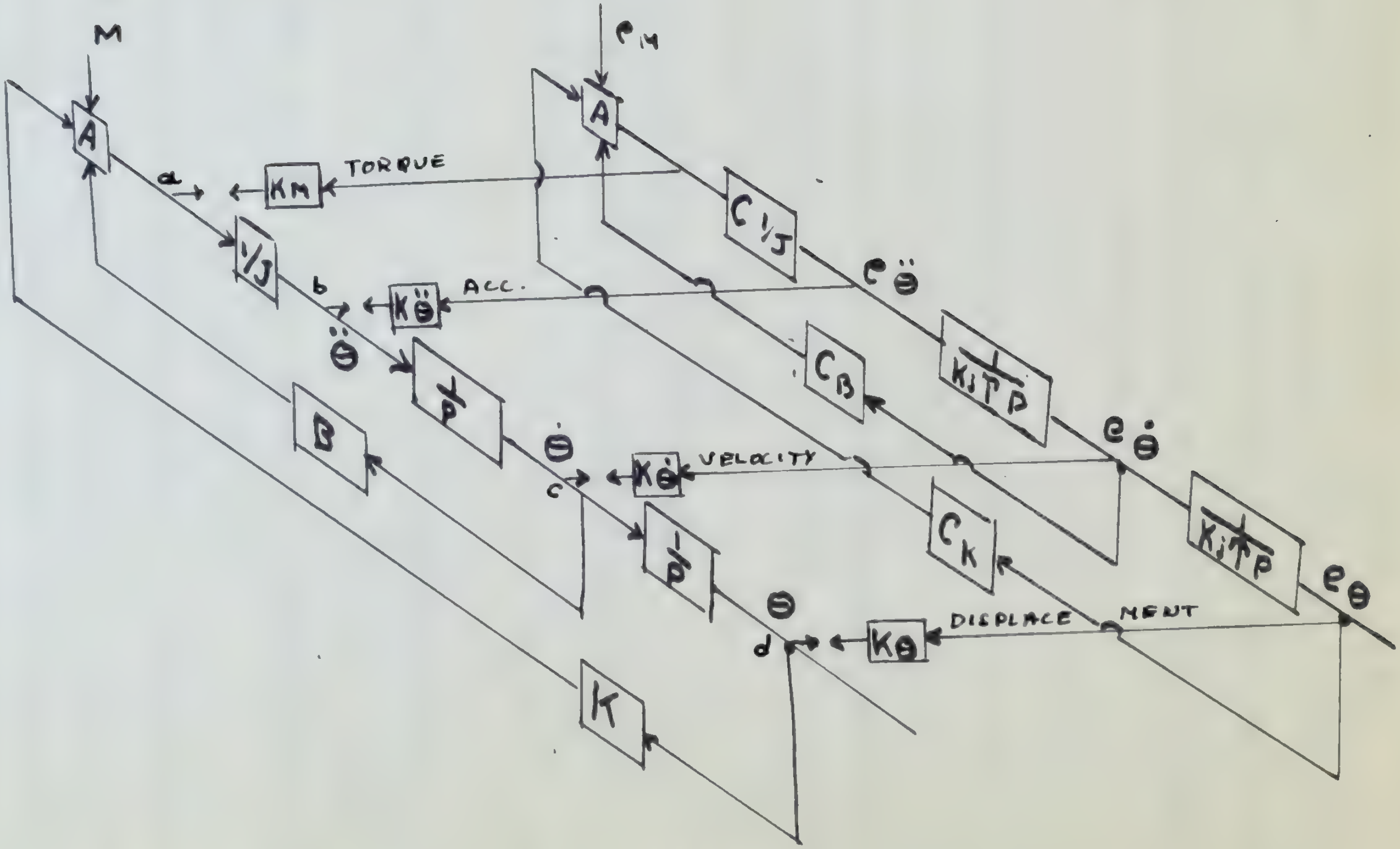


FIG. 15 SCALING DIAGRAM

of rotational velocity. The time variation of e_Θ will be identical to that of Θ. Each voltage scale factor, k, is exactly unity.

It is clear that if it were possible in all cases to set up a real-time analog with all settings identical to the parameters they represent, the interpretations of results would be straight-forward. However, this procedure meets with the following difficulties:

(1) "Fast-time" or"High-speed" may be advantageous or desired.

(2) Parameters of the mechanical system may have values which may not be conveniently set on the computer.

To overcome these difficulties the procedure which follows may be used. Any "real-time" analogue may be easily reduced to a "real-time" computer by defining a new unit of time----.

The asec (for analog-second or not-a-second)

The asec is defined so that the time constant of intefration of the analogue is unity in units of asec.

Thus:

1(asec) = T(sec) and is analogous to one second of real time.

When the analog problem is solved in units of asec, its block diagram will always reduce to that of Figure 15 and the corresponding simplicity of real time interpretation may be applied directly.

The choice of the integrator time constant T in any real problem depends on the convenience and limitations of the computer and display or recording system. In cases where T is fixed and a variation is desired, either an additional coefficient may be used preceding each integrator and be considered part of the integrator, or any coefficient already preseding an integrator may be adjusted to represent both a parameter and a new integrator

time constant. The choice of the optimum T has a bearing on the setting of parameters and is considered in the following discussion.

The reduction of the fast-time analog to a real-time analog by use of the asec solves one difficulty. The second involving the setting of parameters will now be discussed. Two requirements must be met in each setting:

(1) It must be reasonable, lying in the linear accurate range of the coefficient unit.

(2) It must not produce voltage variations which are too large to be handled by the computer or too small to be accurately measured.

Both of these factors are met by the single consideration that all settings be as close to unity as possible. Although this may seem a rather arbitrary requirement, when the action of most real systems in nature is formulated mathematically with an accuracy and significance consistant with the accuracy of measurement and determination of parameters, the so-called loop gains in the mechanical operational block diagram have values near unity.

A practical approach to obtaining coefficient settings near unity is as follows:

Referring to Figure 15, there were defined factors k to convert volts into the appropriate variable. These "k's" all had values of unity in the real-time and asec-time computers.

In most practical cases it will not be possible to set the "k's" at unity. The procedure for determining the values of the "k's" and the coefficients settings is as follows:

From Figure 15 it is evident that, for example, the numerical value obtained by traversing a path from a to b by way of the electrical analog

must be equal to that obtained by going directly from a to b in the mechanical block diagram. The first step in solving for the "k's" is to determine the range of parameters which are expected to be encountered in the physical systems to be investigated. For geared marine propulsion systems this means that one must determine the maximum and minimum values of inertia, spring constants and damping constants, as well as the expected frequency range. The absolute magnitudes of torques and angular deflection will not be important since it is only desired to know at what frequencies the system will resonate and what values of torque amplification will be obtained.

Going from a to b by the two paths indicated above leads to the following equation:

$$\frac{1}{k_m} \times C\frac{1}{J} \times k = \frac{1}{J} \tag{7}$$

Similarly traversal from a to c yields:

$$\frac{1}{K_m} \times C\frac{1}{J} \times \frac{1}{K_jT} \times K\theta = \frac{1}{J}\frac{1}{T} \tag{8}$$

It will be noted that the product k_jT represents the time constant of the integrator, and as noted above this need not be the same for all integrators in the computer.

The equations above, plus enough of the others made possible by alternate traversals, are written so that all coefficients and "k's" appear. Actual maximum values of system parameters are inserted in the appropriate places and a time scale, T, is initially assumed. It will be noted that Figure 15 applies only to a one mass system, however, the computer will consist of four of such blocks with suitable interconnections. This being

the case, a scale solution for one will apply to all.

To continue, an integrator time constant is temporarily assumed, it being noted again that this is equal to $k_j T$. The values for the "k's" in each equation are assumed and the resulting coefficient setting determined. With the type of coefficient setting amplifier used the unity range may be considered to be from 0.2 to 20, though it is desired that the variation be as small as possible. At this point it may be well to remark that the resistors R_1 and R_0 of Figure 6 need not be fixed. One or the other may be variable or they may be replaced by one variable resistor whose tap is equivalent to the junction of the two original resistors. As stated above, such a device has a limited range of accurate setting.

If the settings obtained by the above procedure do not fall in the proper range, the assumption as to the value of one or more of the "k's" may be changed, as may the time constant of the integrator. The values obtained are checked for self-consistency between the various traversal equations and necessary adjustments made. At first glance the process may seem to be fairly long and laborious and to embody much trial and error. However, familiarity makes it possible to make good estimates at the start and the determination of constants and coefficients becomes rapidly convergent.

RESULTS

The computer sections have been designed and construction nearly completed. The computer in its present state can not be tested or operated pending provision of a heavy duty regulated power supply and instrumentation.

It is not anticipated that difficulty will be experienced in placing the computer in operation since the design and construction followed regonized analog computer practice. As mentioned above, the critical d-c amplifiers are provided by the well engineered Philbrick K2-W units.

DISCUSSION OF RESULTS

As stated in the introduction, it was first decided to construct and manufacture a passive element analog, but difficulties in the design of the inductors necessary, as well as other difficulties, forced an abandonment of this approach. Much time and effort was devoted to this line of attack, consequently reducing the time available for the design and construction of the electronic analog.

It is now realized that the design itself is a major undertaking, mechanical construction of the computer imposing an added burden upon available time. It is felt that satisfactory progress has been made since the design itself has been completed and only a small amount of work, compared to what has already been done, is required to complete the computing section.

In the design of the computer it was kept in mind that it would be desirable for it to be easily converted to a general purpose analog computer. The inputs and outputs of all computing elements were therefore brought out to panel jacks rather than being permanently wired in the configuration suitable for typical geared-turbine propulsion system. Space was also provided so that initial condition and reset circuits as discussed in (3), Chapter 7, can be added with a minimum of difficulty. Provision has also been made for the addition of several more K2-W units and their associated circuitry.

It will be noted that the damping factor computing elements operate as resistances independent of frequency, it being possible to select the appropriate values when the computer indicates the frequencies at which the

propulsion system is resonant. Knowing the characteristics of the propeller and shafts used in the physical system, the proper damping factors can be set and the computer will then give accurate values of torque amplification.

Based on experience with other computers of the same general construction as the one which is discussed in this paper, an accuracy of no less than 2% is expected in frequency and amplitude determination. This accuracy can be made to approach 1% if coefficient settings are made by measuring with outside instrumentation rather then relying on the calibration of the scales on the computer.

CONCLUSIONS AND RECOMMENDATIONS

The torsional analog computer has been designed and the computing sections nearly completed. With the addition of a power supply and instrumentation the computer will be ready to make analyses of torsional vibrations in marine geared turbine propulsion systems.

It is recommended that an investigation be made of the feasibility of constructing circuits for generating proper values of the damping factors as the computer operates. Possible lines of attack may be found in (3), Chapter 6.

APPENDIX

SUPPLEMENTARY INTRODUCTION

In the introduction the basic circuits employed in analog computers were illustrated and their operation explained. It will now be shown how these basic circuits are combined to create a complete analog computer.

As has been said, the computer consists basically of four blocks of computing elements as in Figure 15. To these are added other computing elements interconnecting the basic assemblies. To illustrate: the term $K_1(\theta_1 - \theta_2)$ is obtained by taking an input from the θ_1 and θ_2 points of the computer and putting them into a summing coefficient unit. The need for using an actual subtracting unit is avoided by defining θ_2 as negative in its basic block. This causes no difficulties in sign in the rest of the equations. This can be seen by rewriting equation equation (3) as it would be solved in the computer:

$$J_3\ddot{\theta}_3 = +B_3(-\dot{\theta}_3) + B_b(\dot{\theta}_2 - \dot{\theta}_3) - K_2(\theta_3 - \theta_2) \qquad (9)$$

It will be remembered that the computing elements used change the sign of a quantity, and hence one can see that $-\dot{\theta}_3$, for example, appears naturally in the computer. When it becomes necessary to reverse the sign of a whole term containing several quantities it is only necessary to put it through an adder with unity gain. The extension of this method to the rest of the terms in the equations is obvious.

The major difficulty is in correlating the signs of the terms in the physical equations and the way in which they appear in the computer. The problem is solved by having two adding units before each integrating chain in the computer so that the proper sign will be present at the input to the first integrator. It may be noted that the $\frac{C_1}{J}$ element may be used to produce

one sign reversal, the adder indicated producing the other.

DETAILS OF CONSTRUCTION

The data sheets on the following two pages give much pertinent information on the Philbrick K2-W units. It will be noted that the input impedance is extremely high and the output impedance very low. These features permit simple calibration and circuit design since one need not take into account undesired interaction and loading of one circuit by another. Thus it is possible, for instance, to take two outputs from a single amplifier using 100 thousand ohm potentiometers without exceeding the load capacity of the amplifier. It will be found, however that in the computer as designed for the ships propulsion vibration problem, only one such load is imposed at any point, the others being at a much higher impedance level.

The fixed resistors and capacitors used in the construction of the computer are of one percent accuracy. Clarostat type 10 potentiometers were used for coefficient setting. These potentiometers, as calibrated by the George A. Philbrick Researches, Inc., have a total resistance accuracy of one percent and a one percent rotational resistance accuracy. The company has provided coefficient scales suitable for use with these potentiometers.

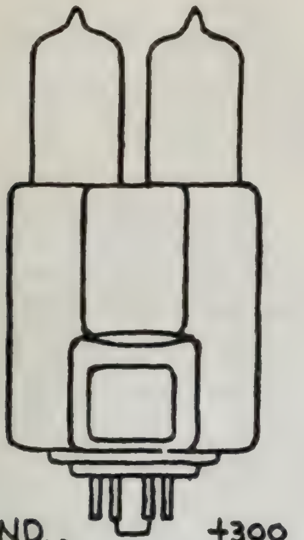
The general method of construction can be observed in the appended photographs. It will be seen that terminal board type construction is used for all signal wiring. Power is supplied to the unit from a power panel on a separate chassis through plugs which mate with female connectors on each computer deck.

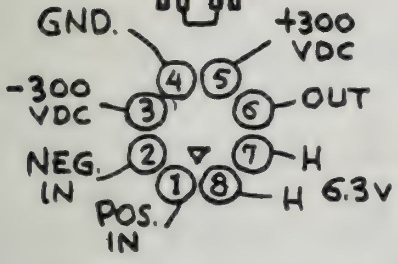
DRAWING NO.

MODEL K2-W

DIRECT CURRENT PLUG-IN AMPLIFIER DESIGNED FOR FEEDBACK COMPUTING IN ELECTRONIC ANALOG SYSTEMS

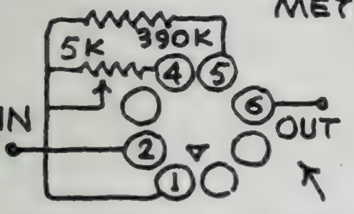
FAST & SLOW





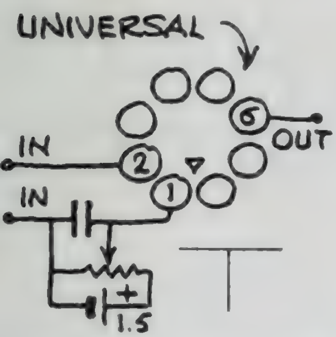
INPUTS:	DIFFERENTIAL PAIR, POS. & NEG. IMPEDANCE OVER 10 MEGOHMS WITHIN OPERATING RANGES.
OUTPUT:	RANGE MINUS TO PLUS 50 VOLTS UNDER LOADS TO 50K OR 1 MA. IMPEDANCE 300Ω WITHIN RANGE.
GAIN:	PLUS AND MINUS 15,000, APPROX.
RESPONSE:	FEDBACK FOR UNITY GAIN; BANDWIDTH WELL OVER 100 KC. RISE TIME APPROX. 2 μSEC.
POWER:	REGULATE VOLTAGES FOR MAX. STABILITY. 6.3 VAC OR VDC AT 0.6 AMPERES + AND −300 VDC AT 5 MILLIAMPS.
BASE:	OCTAL PLUG, WITH KEY ON LINE OF TUBE CENTERS.
WEIGHT:	2.8 OZ. LENGTH: 4.5 INS. OVERALL.

SUGGESTED ZEROING METHODS:



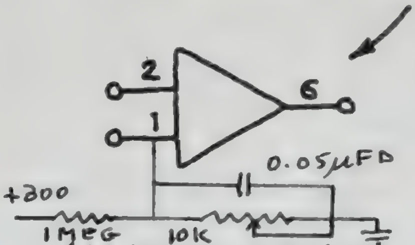
FOR NEG. GAIN ONLY

UNIVERSAL

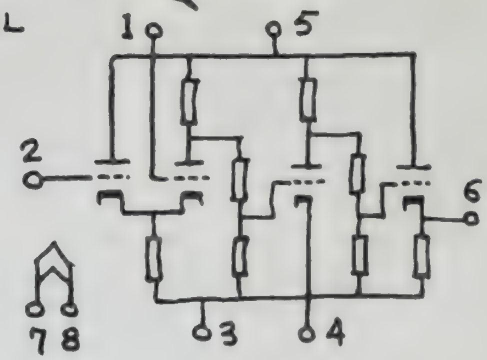


SCHEMATIC DIAGRAM

AMPLIFIER SYMBOL



ALL VOLTAGES ARE WITH RESPECT TO AN IMPLIED GROUND.



JUNCTION SYMBOL

CROSS-OVER SYMBOL

ELECTRICAL NOTES

MECHANICAL NOTES

(UNLESS OTHERWISE SPECIFIED)

TUBES:

2 12AX7

CAPACITORS: INTEGERS — mmf DECIMALS — mf

RESISTORS: K — kilohms, others megs. ½ W. ± 10%

MATERIAL

CASE: MOLDED TENITE 2, SEALED, WITH FINGER GRIP.

TOLERANCES:
FRACTIONS ± 1/64
DECIMALS ± 0.005
ANGLES ±

GEORGE A. PHILBRICK RESEARCHES, INC.,
230 CONGRESS ST., BOSTON 10, MASS.
Analog Computors for RESEARCH & DESIGN

OPERATIONAL AMPLIFIER

DR.

GAP/R

CH.

APP.

SCALE

DRAWING NO.

MODEL K2-W

PRINT RELEASED TO

DATE Sept 15, 1952

Eng. Dept. Form DR-1, August 28, 1949

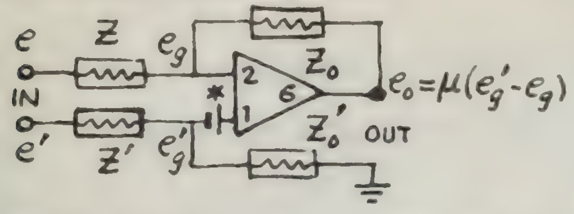
PRINTED BY SPAULDING-MOSS CO., BOSTON, MASS. RE-ORDER NO. S-1487

DRAWING NO.

K2-W CIRCUITS

EFFECTS OF EXTERNAL COMPUTING IMPEDANCES

ASSUMING ZERO GRID CURRENTS,

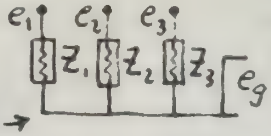


$$\frac{e-e_g}{Z} = \frac{e_g-e_o}{Z_o}, \text{ AND } \frac{e'-e_g'}{Z'} = \frac{e_g'}{Z_o'}$$

WITH μ LARGE, $e_g \doteq e_g'$, SO THAT

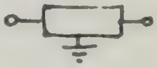
$$e_o = -\frac{Z_o}{Z}\,e + \frac{1+\frac{Z_o}{Z}}{1+\frac{Z'}{Z_o'}}\,e'$$

EACH INPUT MAY BE MADE MULTIPLE. FOR EXAMPLE INSTEAD OF e AND Z ONE MAY USE: →

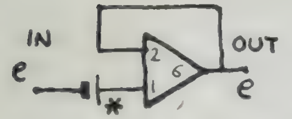


THIS REQUIRES ONLY REPLACEMENT OF $\frac{1}{Z}$ BY $\sum_{i=1}^{3}\frac{1}{Z_i}$, AND OF e BY $\sum_{i=1}^{3}\frac{e_i}{Z_i}$. (SIMILARLY FOR e' AND Z'.)

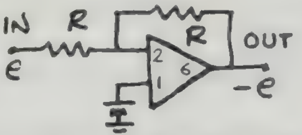
EACH IMPEDANCE ELEMENT MAY BE REPLACED BY A 3-TERMINAL NETWORK:



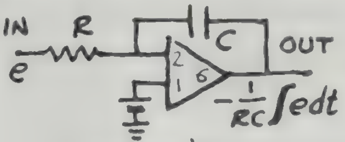
⑪ SUGGESTED INDIVIDUAL APPLICATIONS



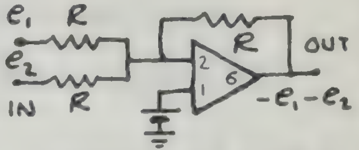
VOLTAGE FOLLOWER



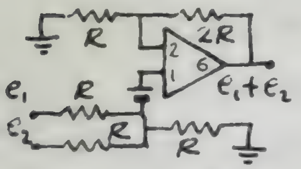
SIMPLE INVERTER



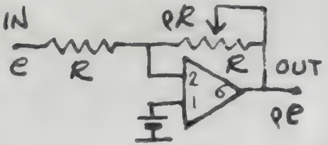
TIME INTEGRATOR



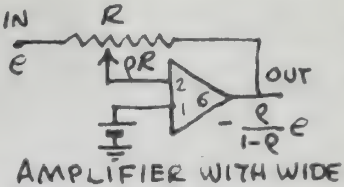
INVERTING ADDER



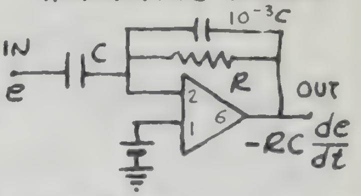
DIRECT ADDER



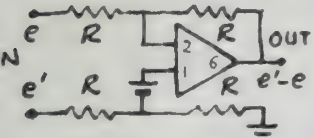
AMPLIFIER WITH LINEAR GAIN ADJUSTMENT



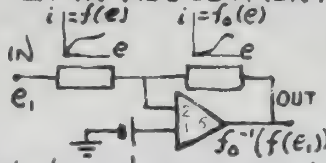
AMPLIFIER WITH WIDE-RANGE GAIN ADJUSTMT.



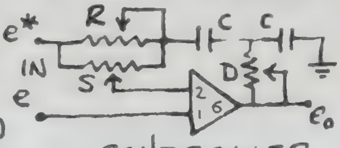
TIME DIFFERENTIATOR



SUBTRACTOR



NONLINEAR VOLTAGE TRANSF.



"CONTROLLER MECHANISM"

e: FROM MEAS. VARIABLE
e*: DESIRED VALUE OF e
e_o: TO MANIP. VARIABLE
S: SET SENSITIVITY
R: SET RESET RATE
D: SET DERIV. EFFECT

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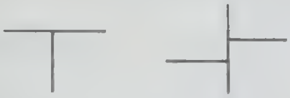
1. J. R. RAGAZZINI et al, ANAL. of PROBS. IN DYNAMICS BY ELEC. CIR., PROC. IRE, May 1947
2. G. A. KORN, ELEMENTS OF DC ANALOG COMPUTERS, ELECTRONICS, April 1948
3. RECENTLY OF INTEREST IN ELECTRONICS: Oct. 1951, p. 128; April 1952, p. 147, Aug., p. 144
4. CATALOG & MANUAL ON HIGH-SPEED ALL-ELECTRONIC ANALOG COMPUTORS...



JUNCTION SYMBOL

CROSS-OVER SYMBOL

ELECTRICAL NOTES
MECHANICAL NOTES
(UNLESS OTHERWISE SPECIFIED)

TUBES:
* SEE SUGGESTIONS FOR BIASING ON GAP/R MODEL K2-W DATA SHEET, BUT NOTE ... FOR MANY USEFUL PURPOSES, BIAS MAY BE OMITTED IN THE ABOVE.
CAPACITORS INTEGERS — mmf
DECIMALS — mf
RESISTORS: K — kilohms, others megs.
1/2 W. ± 10%

MATERIAL
$50k\Omega \le R \le 10M$
$0.0001\text{ mfd} \le C \le 10\text{ mfd}$
TOLERANCES
FRACTIONS ± 1/64
DECIMALS ± 0.005
ANGLES ±

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COMPUTING CIRCUITS FOR K2-W

DR GAP/R
CH
APP.
SCALE
DRAWING NO.
K2-W CIRCUITS

PRINT RELEASED TO
DATE Sept. 20, 1952

Eng. Dept. Form

To simplify circuit tracing and future additions to the computer all wiring has been color coded as follows:

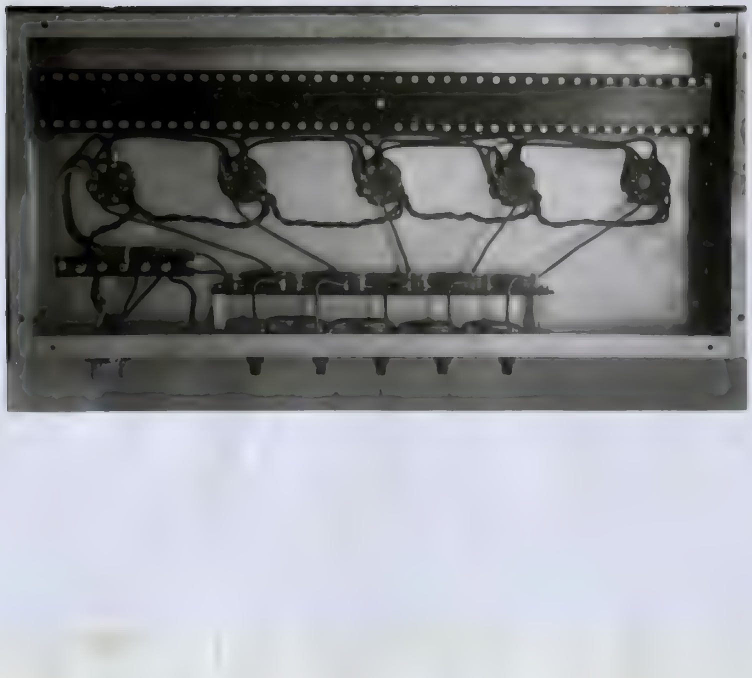
Green	Computing signals
Red	Plus 300 volts
Yellow	Minus 300 volts
Black	Ground
Black (twisted pair)	6.3 volt filament supply

It will be noted the filament wiring is of twisted pair construction and is isolated from other wiring as much as possible in order to eliminate hum pickup by the signal wiring.

At the rear of the chassis can be seen the zeroing circuits. These have been placed in this position since adjustments will be infrequent once the computer has been warmed up and stabilized. The method used for zeroing in this computer has been indicated on the center diagram of the first data sheet.

The high voltage power supply's requirements for the computer assuming 25 computing elements are rather rigourous. First, it's output impedance should be on the order of one or two ohms to prevent coupling between amplifiers through the power supply. Second, the plus and minus 300 volts should be regulated to at least one half of one percent to maintain good stability in the computer. They should each be capable of supplying approximately 150 milliamperes. A minimum of 15 amperes at 6.3 volts will be required for the filaments, a supply capable of supplying 20 or more amperes would be desirable.

As for instrumentation, the desired voltages can be read using almost



any good quality vacuum tube a-c voltmeter. However, it must be borne in mind that the usual commercial instruments have an accuracy of only two or three percent and must be calibrated against a laboratory type instrument if overall accuracy available in the computer is to be obtained.

CALCULATION OF COEFFICIENT SETTINGS

To obtain estimates of system variables on which to base coefficient settings, the plant of (1) was used with generous margins.

$J_{max} = 1{,}000\ (10^3)$ in-lbs-sec^2

$J_{min} = 50\ (10^3)$ in-lbs-sec^2

$K_{max} = 500\ (10^6)$ in-lbs-rad

$K_{min} = 30\ (10^6)$ in-lbs-rad

$B_{max} = 25\ (10^6)$ in-lbs-sec/rad

As a preliminary step the integrater time constant was picked as $T = 0.04$ and K_m as $10^5\ \frac{\text{in-lbs.}}{\text{volt}}$

A traversal from a to b gives:

$$\frac{1}{K_m} \times C_{\frac{1}{J}} \times K\ddot{\theta} = \frac{1}{K}$$

$$\frac{1}{10^5} \times C_{\frac{1}{J}} \times K\ddot{\theta} = \frac{1}{10^6}$$

$$C_{\frac{1}{J}} \times K\ddot{\theta} = \frac{1}{10}$$

As a trial pick an arbitrary range of J as 0.2 to 20 which may be accurately set. The 0.2 setting applies at this point. Therefore we get

$$K\ddot{\theta} = \frac{1}{2}\ \frac{\text{rad/sec}^2}{\text{volt}}$$

The path from b to c gives:

$$\frac{1}{K_{\ddot{\theta}}} \times \frac{1}{K_J T \phi} \times K_{\dot{\theta}} = \frac{1}{\phi}$$

$$K_\theta = K_\theta\,(K_jT) = 0.5(0.04) = 0.02\ \frac{\text{rad/sec}}{\text{volt}}$$

Going from c to d yields

$$\frac{1}{K_\theta} \times \frac{}{K_jTp} \times K_\theta = \frac{1}{p}$$

$$K_\theta = K_{\dot\theta} \times K_jT = 0.02(0.04) = \frac{0.0008\ \text{rad}}{\text{volt}}$$

To get C_K, a traversal yields

$$\frac{1}{K_\theta} \times \frac{}{K_jTp} \times C_K \times K_m = \frac{K}{p}$$

$$\frac{1}{0.02} \times \frac{1}{0.04} \times C_K \times 10^5 = 500(10^6)$$

$$C_K = 4 \text{ for max}K$$

$$= 0.3 \text{ for min}K$$

For C_B:

$$\frac{1}{K_\theta} \times C_B \times K_m = B$$

$$C_B = \frac{BK_\theta}{K_m} = 5 \text{ max}$$

All settings are thus in the region of 1 and hence are satisfactory.

LITERATURE CITATIONS

(1) Powell, S. C. and Bassett, W. V., "Practical Aspects of Torsional Vibration in Marine Geared-Turbine Propulsion Units", TRANSACTIONS of The Society of Naval Architects and Marine Engineers, Vol. 52, 1944, pages 65-90.

(2) Concordia, C., "Network Analyzer Determination of Torsional Oscillations of Ship Drives", TRANSACTIONS of The Society of Naval Architects and Marine Engineers, Vol. 51, 1933, pages 51-60.

(3) Korn, G. A. and Korn, T. M., "Electronic Analog Computers", McGraw-Hill Book Company, 1952.

(4) Reswick, J. B., "Functional Block Diagrams and Scale Factors--Applications to the Philbrick Type Analog Computer", Dynamic Analysis and Control Laboratory, M. I. T., File, March 20, 1953.

(5) Philbrick, G. A., "Dimensionless Scale Factors, an Informal Elementary Discussion", George A. Philbrick Researches Co., Inc., Boston, Massachusetts, November 1952.

(6) Reswick, J. B., Dynamics - 2.07 Notes, M. I. T., 1952.

(7) Powell, S. C., "Torsional Critical Speed Investigation for Main Propulsion Units, CA 68-75", Design Sketch, Bethlehem Steel Co., Fore River Yard, 1942.

(8) Gardner, M. F., and Barnes, J. L., "Transients in Linear Systems", Vol. 1, John Wiley and Sons, 1942.

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